Renewable and Sustainable Energy Reviews 25 (2013) 660–669

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

# The promise and the performance of the world's first two zero carbon eco-cities

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ARTICLE INFO

*Article history:*
Received 18 February 2013
Received in revised form
7 May 2013
Accepted 13 May 2013
Available online 7 June 2013

*Keywords:*
Eco-city
Zero-carbon
Zero-waste
Zero-emission
Renewable energy

ABSTRACT

In recent years two major attempts have been made to develop 'eco-city prototypes' the Dongtan City in China and the Masdar City near Abu Dhabi. Both attempts have revolved round the premise that advanced post-modern technology, innovative urban planning, reliance on renewable energy, and emphasis on 'total' reuse can combine to achieve 'zero carbon–zero waste' existence. The plan of the two cities had also integrated strong business interests into the system, aiming to make 'zero carbon–zero waste' a kind of catch-phrase or a fashion statement that would enhance the value of the real estate the two eco-cities were planning to offer.

The paper recapitulates the objectives that were set and assesses the present status of realization of those objectives. There is an already substantial and widening gap between the promise and the performance in both the cases; the review identifies the gaps and the possible reasons of their occurrence. It is highlighted that the expectation of a zero-waste existence is inherently flawed because the Second Law of Thermodynamics makes it impossible to attain.

The paper brings out that no 'eco-city' concept can be translated into reality unless and until the inhabitants of the eco-city are prepared to voluntarily and consistently observe certain restrictions on resource consumption and to sacrifice some of the basically illusory but highly fancied 'comforts' which drive consumption in conventional habitations. It follows that many of those measures that are sought to be introduced in the eco-cities to make them cleaner and greener can very much be implemented in existing cities if only the same extent of voluntary participation from the lay public can be invoked that is expected in the 'eco-cities'.



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## 1. Introduction

Living within fully closed material cycles—in other words living in a way that incoming solar energy is the only source of all energy consumed and no material is 'wasted'—is an enchanting dream.

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http://dx.doi.org/10.1016/j.rser.2013.05.011

This dream was initially, and still is, pursued by space scientists [1–3], who aim to create human-centric mesocosms or 'life-support systems' within spaceships [4–6]. The hope has been that such mesocosms would enable human beings to live for several months or years on spaceship even when there is no possibility to supply them with the life's essentials from the earth, and when solar radiation is the only external source of energy available [3,7].

The tides of environmental consciousness that began sweeping across the world from the late 1960s onwards generated interest in the protection of the earth's ecosystems and the dream of 'zero waste' existence began to be pursued for terrestrial living as well [8]. But before mankind could develop a single truly 'zero waste' technology it is being challenged by the existing-threatening rise in global warming. This has led the catch-phrase to be modified into 'zero waste—zero carbon' existence.

Whereas attempts to set-up 'zero emission' buildings—such as the Adam Joseph Lewis Center at Oberlin College, Ohio, [9] 'zero emission' villages—such as the bioenergy village Juhnde, Germany [10,11] and low emission townships—such as the New Songdo City, South Korea [12,13] have been made from time to time. The Dongtan and the Masdar City projects have distinguished themselves by the scale of 'clean living' they had aimed to achieve when they had begun.

This paper charts the history of the two eco-cities. It begins with a recapitulation of the eco-city concept and then discusses the two eco-cities from the point of their conceptualization to the present state of their development.

## 2. The eco-city concept

The term 'eco-city' was reportedly coined during the winter of 1979–80 by the members of a voluntary organization Arcology Circle [14]. The term features prominently in a 1987 book [15] and is used interchangeably with the term 'sustainable city' [16]. The concept was proposed way back in 1898 [17–19] in the name of 'garden city' and has been described [20] as a city which 'is organized so as to enable all its citizens to meet their own needs and to enhance their well-being without damaging the natural world or endangering the living conditions of other people, now or in the future'.

Given that terms like 'sustainable', 'clean', 'green', or 'zero-emission' living are used rather fuzzily in scientific literature, often meaning different things in nature or degree to different authors, it is difficult to give a precise definition to the derived terms like 'sustainable city' or 'eco-city' which are themselves derived from imprecise terms [20]. The following ten attributes have been assigned to eco-cities [21,22]; they—

(1) should have land-use priorities such that it creates compact, diverse, green, and safe mixed-use communities around public transportation facilities;
(2) should have transportation priorities such that it will discourage driving and emphasize "access by proximity";
(3) should restore damaged urban environments;
(4) should create affordable, safe, convenient, and economically mixed housing;
(5) should nurture social justice and create improved opportunities for the underprivileged;
(6) should support local agriculture, urban greening, and community gardening;
(7) should promote recycling and resource conservation while reducing pollution and hazardous waste;
(8) should support ecologically sound economic activities while discouraging hazardous and polluting ones;
(9) should promote simple lifestyles and discourage excessive consumption of material goods;
(10) should increase public awareness of the local environment and bioregion through educational and outreach activities.

In a word, a sustainable city should be able to feed itself with minimal reliance on the surrounding countryside, and power itself with fully renewable sources of energy, thereby creating little or no ecological footprint. A sustainable city would use land with maximum possible efficiency and cleanliness, generate minimum possible waste and then fully recycle and reuse what it does generate. It would offer more space for people in a scenic, safe, quiet, rejuvenating and healthy environment.

These are all noble goals of an utopian existence and are certain to benefit humankind if only humankind can create and maintain the utopia. But wisdom of hindsight tells us that there are far too many cross-currents, layers, hues, aspirations, perceptions, and the resultant conflicts in the human societies to maintain any ideal state for long. Even the perceptions of what is ideal vary greatly from individual to individual, society to society, region to region in both time and space [20,23–25].

Interestingly many features which an eco-city is sought to have are the ones which have distinguished rural existence down the ages [24,26]. Classically, rural settling patterns have been such as to provide easily walkable access of the residential dwellings to public utilities like shops, schools, and prayer-houses. Villages have also relied almost exclusively on renewable energy in the form of biomass or biomass-derived charcoal as fuel, windmills, and watermills [7]. There was proximity to nature; wildlife and forest produce were used for human benefit but with sufficient moderation for it to remain sustainable. The relatively less sedentary and more socially well-knit existence generated lesser life-style diseases of the body and the mind. The village itself produced most of what it consumed and disposed its waste locally. Most of the biodegradable waste—which now goes to trash bins and then landfills or incinerators—was composted and returned to soil. The villages existed in a low-carbon, low-waste mode if not a zero-carbon, zero-waste one. The only apparent difference is that the eco-cities aim to realize all the positive features of a rural existence and yet aspire to maintain the dizzying pace of economic advancement which has brought great development alongside great eco-degradation in megacities like Shanghai and Mumbai. The cities of Dongtan and Masdar were conceived to achieve the union of the two apparently irreconcilable growth models.

## 3. Dongtan city, China

Dongtan was the first to break ground. In the publicity blitz that was mounted in 2005, Dongtan was projected as the 'world's first-ever zero carbon eco-city' [27,28]. At its initiation, on 9 November 2005, when China's Shanghai Industrial Investment Company (SIIC) and the British firm Arup signed an agreement to develop Dongtan, the British Premier and the Visiting Chinese President were in attendance [30]. This underscored not merely the uniqueness of the Dongtan initiative but the enormous profitability such a venture was perceived to carry at that time in terms of generating a hugely attractive and novel brand image.

The location chosen for Dongtan was the 86 $Km^2$ Chongming Island which is situated at the mouth of the mighty Yangtze River [27,31]. Like all other small islands, Dongtan also sports very rich and *fragile* ecological sub-systems. Its 6.3 $Km^2$ marshy eastern tip which was identified to be developed first, as a 'demonstration zone' for what the Dongtan eco-city concept stood for, is a migratory stop for several rare and threatened avifauna [32–34], including one of the rare water-bird species in the world—the black-faced spoonbill [14,35]. But this was not the reason for the choice of the Dongtan site; it, rather, was the Chongming Island's

close proximity to one of the world's fastest growing super-cities: Shanghai. If Shanghai which is the largest city of the world's most populous country, is distinguished by its great size and the finesse of its infrastructure, it is also recognized as one of the most polluting of the world's megapolices [27]. An eco-city in the outskirts of Shanghai was expected to project China's concern for its contribution to the global carbon emissions as well as its desire to alter the paradigm of its future development towards much greater sustainability. In a way, Dongtan was not only expected to show the rest of the world ‘a shape of cities to come’ but also lead the world towards it.

Dongtan's planning was envisaged to achieve the following nine objectives to make Dongtan a ‘truly eco-city’ [28]:

1. Environmental protection
2. Social and economic benefit
3. Low ecological footprint
4. Water and flood management
5. Agricultural production
6. Energy production, use and emission reduction
7. Green city
8. Accessibility and transport
9. Resource and waste management

The planners, Arup, even developed a model they called an ‘integrated resource model’ to reveal how each change made in one system at Dongtan would ripple across the city plan and affect those systems that integrate with it (Fig. 1). The model was expected to help them in comparing the inputs and outputs of any facility, process, product, or human activity on the island. For example, if they were to move an office park a kilometer in a given direction, the tool would recalculate average walking distances for commuters, estimate how many people will drive or take public transit instead of walk, and then add up the ultimate change in energy demand. The tool was also expected to allow the planners to identify places where one process may create waste that another process could recycle [29].

A slew of measures were planned to meet these goals (Table 1) and no stone was thought to be left unturned in the process. It was aimed to ban all fossil-fuel powered cars and design a habitation where one can get around using electric cars, bicycles, or just legs [27]. Innovative ‘water taxies’ were thought of, which would ply in scenic canals instead of roads [36], and buses powered by fuel cells [14]. It was aimed to recycle as much as possible, including all wastewater; grow food on its own environmentally sensitive farms; and create all its own energy in non-polluting ways–wind, solar, and the burning of human and animal waste. It sought to encourage the use of novel building materials, such as a concrete like substance that can be made from ash and used cooking oil. By combining urban planning, urban design, sustainable energy management, economic and commercial planning and even community development schemes, into a cocktail of ‘integrated urbanism’ [29,37], Dongtan wished to became the first eco-city and zero carbon city in the world. Even a hydrogen energy grid system, the first of its kind in China, had been proposed.

To emphasize that Dongtan was not being planned as a mere show-piece but a dynamic nucleus which will stimulate all future urbanization along similarly ‘clean and green’ lines, it was planned to set up a Dongtan Institute for Sustainability [14]. The aim was to make it an international center of excellence for the study of the environment. Initially the institute's focus was to be on teaching, research and consultancy but over time it was to aim at developing spinoff businesses around it as there are around the campuses of the Harvard University and of Massachusetts Institute of Technology (MIT) in Boston, USA.

All-in-all Dongtan was expected to become a showcase for technologies and urban design that help to protect the environment while maintaining economic growth and social development. Its importance was further underlined when it was proclaimed as ‘China's ten most influential planning projects for the future’ [38].

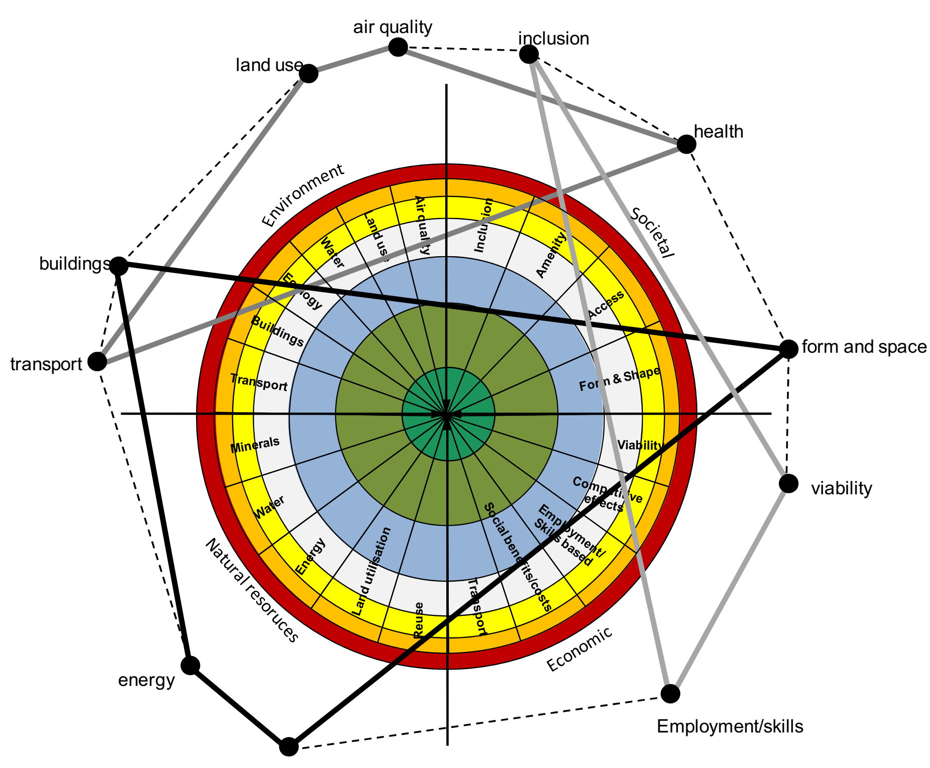



**Fig. 1.** The ‘integrated resource model’ developed to assist the planning of the Dongtan eco-city [29].

**Table 1**
Different aspects of the Dongtan strategy ([29,36,37].

| Aspect | The Dongtan strategy |
|---|---|
| Town planning and buildings | • The city would be laid out in a way as to reduce infrastructure costs, reduce transportation costs, improve amenity, and improve energy efficiency.<br>• Building density will be optimized to allow for pedestrian neighborhoods and efficient heating and cooling systems, without overburdening the island's soft soil.<br>• Shall be constructed with sustainable and low-cost materials, such as wood from replenished sources as far as possible.<br>• Sun and shade will be optimally utilized in the streets and homes will be laid out for the best use of sun and shade. |
| Energy generation and conservation | • The city will be self-sufficient in energy, meeting all its requirements with renewable sources: solar, wind, and biomass. Further, the energy demand will be reduced by 64% by appropriate technological interventions, saving 350 000*t* of $CO_2$ emissions per year.<br>• The remaining emissions shall be offset by sequestration via planting trees and other means, to achieve a net zero emission existence.<br>• A combined heat and power plant (CMP) will be fueled by rice husks, and biogas will be produced from the treatment of municipal solid waste (MSW) and sewage. The CMP would be placed in the city center with radially outgoing pipes feeding the heat energy to most buildings.<br>• Buildings will be naturally ventilated and properly insulated, with turf and vegetation covering their roofs, which will serve as a natural form of insulation.<br>• Materials with low embedded energy will be employed and the streets and homes shall be designed for the best use of sun and shade to reduce energy consumption.<br>• Meters will display energy consumption and generation in each house to enable residents to monitor their real-time energy use. Upto reasonable limit energy will be low priced; beyond the limit it will become incrementally costlier. |
| Water management | • Water consumption will be reduced by 43% and water discharge by 88%, without compromising on the quality of water usage.<br>• A dual piping system will run throughout the city; one pipe at each point providing water for potable use and the other pipe providing reclaimed water for toilet flushing and farm irrigation.<br>• Green rooftops will play an important role in meeting the city's water demand through collecting and storing rainwater. |
| Waste management | • All waste shall be collected and processed.<br>• It will be a near zero waste city. MSW will be sorted and up to 80% will be recycled.<br>• Organic waste and human waste will be digested and composted; the resulting biogas shall be used as energy source and the compost as a fertilizer for local farmland. |
| Transportation | • It will have no transport-related carbon emissions.<br>• The city will be connected by bike routes and public transport corridors, allowing residents to access different parts of the city by tram, bus, bicycle, and on foot.<br>• The streets of the city will be laid out such that walking or cycling to work shall be quicker than driving; it will take $<7$ min to walk from any part of the city to a public transportation stop/station.<br>• Shared zero-emission commercial delivery trucks will be used for transporting goods throughout the city.<br>• The city will be connected to Shanghai by a 19 km bridge-tunnel to minimize commutation distance between Shanghai and Dongtan.<br>• Gas and diesel vehicles will be banned in the city, and all vehicles and boats used within the city will be powered by battery or hydrogen fuel cell.<br>• Visitors will park their cars outside the city and use public transportation systems within the city.<br>• Over a longer term hydrogen-based transportation shall dominate for which hydrogen filling stations shall be installed. |
| Food supply | • Needs of food shall be met by local farming and fishing communities.<br>• Sophisticated organic farming techniques linked to the waste and sewage recycling systems shall be used to create a sustainable cycle of local food production.<br>• Composted organic wastes will be returned to the local farmland to maintain the long-term soil fertility and production capacity.<br>• Organic vegetables shall be grown with hydroponic techniques in underground plant factories illuminated with solar-powered LEDs to generate as much as six times more produce per acre than conventional farming. |
| Eco system management | • The existing wetlands will be enhanced by returning agricultural land to a wetland state to create a $>3.5$ km buffer zone between the city and the mudflats.<br>• Only around 40% of the land area of the Dongtan site will be developed to urban areas, with the rest dedicated to farms, parks, and wetlands, preventing pollutants (light, sound, emissions and water discharges) from reaching the adjacent wetland areas.<br>• There will be a per-capita green area of 27 $m^2$.<br>• A variety of native vegetation will be introduced to line canals, streets, and rooftops, which will attract butterflies, insects and birds into the city. |
| Socio-economic development | • It will have a diverse population, affordable housing, at least 30,000 jobs on the spot, schools and a hospital, to ensure that it doesn't become dependent on Shanghai.<br>• It will be partly a tourist attraction, and up to 50,000 jobs in tourism and research will be generated.<br>• There will be employment opportunity for the majority of people who live in the city across all social and economic demographics.<br>• There will be policy incentives to attract companies to Dongtan and to encourage people to live and work in the city.<br>• Eco-industry (waste management, wind and solar technology) will be a major component of Dongtan's economy. |

## 4. Masdar city, Abu Dhabi

Even as the Dongtan city plan was bracing to take off, still more ambitious plan of an eco-city was announced by the government of Abu Dhabi–Masdar city [39,40]. It came within months of the grand initiation of the Dongtan plan. If Dongtan's catch phrase was 'world's first-ever zero carbon eco-city', Masdar's publicity blurb went much further by promising to build 'world's first-ever zero carbon–zero

waste city' [20,41–44]. The Masdar City was planned to come up in a 7 Km$^2$ area about 17 Km downtown Abu Dhabi with an initially estimated cost of US$ 22 billion (now about $ 24 billion). On completion it was expected to house 50,000 people and support a floating population of additional 40,000 people. It was to accommodate 1500 business offices and a post-graduate university [45].

'Masdar' means 'the source' in Arabic and is the name of a state-controlled renewable energy (RE) company [46–48]. Its aim is to bring as much contribution of RE to the energy basket of Abu Dhabi as possible besides fostering development of RE technology for use by the rest of the world [45,48,49]. Masdar's initiatives include carbon management under the United Nation's (UN) clean development mechanism (CDM) framework, setting up RE-based power plants and running the Masdar Institute (MI). MI is a university being developed in collaboration with the Massachusetts Institute of Technology (MIT) with focus on the science and engineering of advanced RE. When announced Masdar City was (and still is) Masdar's most flamboyant project: a kind of a township-cum-laboratory which will serve as a place to develop new technology as well as to test its efficacy; 'a living lab for greener, cleaner future' [50].

Even though the ground reality now is much different from what was envisaged [20,30,51,52]. Masdar City is still referred in most reports as what its founding fathers had initially projected it to be–a 'zero carbon–zero waste habitation' which will enable a 'zero-waste lifestyle' and provide a 'zero carbon comfort' [47,53,54]. To many the city is still expected to 'set a benchmark that will ultimately support sustainable development throughout Abu Dhabi and the (South-west Asian) region and provide a functioning blueprint for sustainable living around the world'[49]. Masdar City is continued to be portrayed as leading an urban renaissance [55]. The 'zero carbon–zero waste' catch phrase has caught on so much that every paper written on Masdar city, and an increasing number of papers written on sustainable living, have been repeating this phrase as if it represents something that is scientifically and technologically feasible [16,49,56,57].

### 4.1. Distinguishing features of Masdar city

The team of planners who conceived Masdar City–Foster+Partners–are different from the ones (Arup) who had charted the Dongtan plan. Yet there are a number of similarities in the two plans, the major difference being that Masdar's has been more ambitious.

When it was announced, Masdar City had also intended to make do entirely without fossil fuel use. For its energy needs it was also to rely exclusively on a mix of renewable sources including solar thermal, photovoltaic, and wind [39,40,58]. It was to later augment its needs with geothermal energy and hydrogen energy; the latter was expected to come from Masdar's project on conversion of natural gas to hydrogen and $CO_2$, (with concomitant underground storage of $CO_2$ for enhanced oil recovery [49]. As was planned in Dongtan, all vehicles running on fossil fuels were thought to be kept out of bounds to exclude the use of fossil fuels inside the city. Instead, a battery-powered auto-piloted 'personal rapid transit' (PRT) system was planned [53,59]. The city was designed to be raised 7 m above ground on concrete stilts to make room for the PRT. The PRT system was to consist of sleek four-passenger vehicles which were to run on electric motors. It was to be so designed that once an individual or a small group were to board a vehicle and select a destination, the vehicle would proceed automatically to the destination without stopping. There were to be no tracks—the cars were expected to be autonomous, driven by a computer that was to chart direction with the help of tiny magnets embedded in the road. The idea was that when a PRT car would sense another vehicle waiting in its parking space, it would stop and wait for the area to clear, avoiding a collision [40].

All water to be used in Masdar was planned to be fully recycled. Sewage was to be treated and some of it processed into 'a dry renewable fuel' for generating electricity [39,40,46]. As in Dongtan it was planned to have vacuum tubes under the city to transport garbage to a central location, where it was to be sorted, and as much as possible was to be recycled. The portion that could not be recycled was to be converted to energy through a gasification process and the leftovers were to be incorporated into building materials [60]. The brains trust of the Masdar City had enthusiastically, but unrealistically; assumed that all this will be possible without any net emissions. An executive had even said, "we are hunting down every molecule of carbon dioxide" [39].

The *piece de resistance* of Masdar City was (and still is) its fusion of the concept of traditional Arab architecture and town planning with the post-modern concept of intelligent buildings that seeks to minimize energy and material use. The city is to have narrow, tree-lined, streets with closely spaced buildings shading each other from the scorching desert sun [60]. The buildings are to be oriented to minimize cooling loads [61]. Horticulture is to be so planned as to achieve the most favorable ecosystem services trade-off [62]. Walls will have vents to let the hot air escape and support wind movement that would have a cooling effect [40]. In essence Dongtan had also set out to do something similar: get the best out of the traditional wisdom of that region which the conventionally growing cities like Shanghai had overlooked.

The buildings of Masdar City also aim to utilize energy-efficient construction material. They aim to have their outer layers coated with state-of-the-art sunlight reflectors and heat insulators. Windows would have shades angled to avoid direct sunlight, providing light without heat; the design will be such that it would ensure adequate privacy for the occupants of the residential buildings [40]. There's even a tall (45 m) 'wind tower—inspired by traditional Arabic design, and is similar to the well-known tower installed in Bahrain—that will capture upper-level winds and direct them to the square at its base, cooling the streets [60]. The tower is fitted with LED lights that run down its spine and is intended to signal the level of energy use: blue would mean Masdar City is within its goal of using 50% less energy than a comparable settlement. Red would mean consumption overshot calling for a voluntary load-shedding [39,40,47].

Just as Dongtan was planned to become a hub of world-class education, research, consultancy, and above all, business in 'zero-carbon urbanization,' Masdar City was also positioned to become a 'model for the rest of the world to emulate'. To achieve such a goal, if Dangtan had wished to set up the Dongtan Institute of Sustainability (DIS), Masdar City decided to start the Masdar Institute (MI). MIT has featured in MI's vision too, as it had done in DIS's; more directly this time as MIT is a formal partner of MI, assisting the latter in becoming the Middle East's first graduate research institution dedicated to renewable energy and environmental technologies [30,47].

## 5. The present status

If there were striking similarities between the visions of the Dongtan and the Masdar cities, the swiftness with which the former has crumbled and the second is rapidly losing sheen is also similar. So are the factors that have turned great expectations into expensive disillusionment.

The basic problem, as elaborated in the following section, has been the sheer impracticality of attaining 'zero carbon–zero waste' existence. The second Law of Thermodyramics makes such an

existence impossible because there can never be any machine that can utilize all the energy given to run it nor can there be any process that can operate without wasting some material or energy. The corollary is that more goods we produce, more energy we consume, more waste we generate. A ‘lesser-carbon lesser-waste’ existence is much more plausible but there are two major hurdles in the path of attaining it: high initial costs and low investor acceptance. The second hurdle compounds the first: unless the investors are prepared to tone down their present life-style based on conspicuous energy (and material) consumption and adjust to the restrictive conservation-oriented eco-cities, it is not possible to make any headway in eco-city development.

There were location-specific problems, too. For example a policy of the Chinese government by which no agricultural land can be used for residential or other purpose unless an equal span of land is dedicated for agriculture elsewhere, came in the way of Dongtan city getting started—it was difficult to find ‘replacement land’ for the area that was needed to set up Dongtan city on what is, otherwise, predominantly agricultural land [28]. It was also discovered, as stated earlier, that Dongtan provided wintering ground for one of the rarest birds in the world—the black-faced spoonbill [14]. Even otherwise Dongtan City's location, at eastern tip of Chongming Island in the Yangtze river, encompasses an ecologically sensitive area already under stress [38,63–67] especially the salt marshes which play a crucial role in the spawning success of several species of fish. These aspects made one wonder whether the rise of Dongtan City, albeit in a low-carbon, low-waste manner, will not stress the island's fragile ecosystem beyond tripping point.

But some of these problems would perhaps have been surmounted (and some ignored) had there been a likelihood of significant economic benefit accruing in the long run. But every step taken in the direction of translating the Dangton master plan has brought forth in increasing relief the sad reality that low-carbon low-waste life-style does not come cheaper than a fossil-fuel driven consumerist life-style as long as one persists with the paradigm of development and measures of ‘comfort’ associated with the latter. As a result, the Dongtan dream faded rather quickly [52,68]. As for Masdar City, its vision is still being pursued but it has already been toned down significantly [20,30] and more downsizing is likely. The original plan had six development phases, beginning with the setting up of the Masdar Headquarters, the Masdar Institute, and the initial residential, office and community infrastructure. The full build out was expected by 2016. But now the construction finish date has been advanced to 2025–2030 [69]. The plan to generate all power on-site has been altered, so is the plan to exclusively use renewable energy and computer-driven personal transit pods [61].

Interestingly Masdar's think-tank now believes that it made no sense, either commercially or from an eco-sustainability perspective, to insist on the original zero-carbon, zero-waste goals [30]. They have now realized that the current technology would make achieving such targets enormously expensive and thus largely irrelevant as a model for other sustainable urban development projects. As a consequence many of the original plans, including the one which had aimed at constructing the ‘world's first building that would produce more energy than it consumes’, have been shelved [70]. The extent of development that has occurred so far in Masdar city is futuristic and pleasing [60,61] but is a far cry from being exceptionally low-carbon or low-waste [69]. Less than 10% of the original master plan has been realized and not many more than 100 people are living in the eco-city at present [20]. Masdar city is far from even its drastically toned-down goal of becoming “one of the most sustainable, visually stunning, and livable developments on earth” [71].

## 6. What went wrong?

Even though terms like ‘zero-waste existence’ and ‘zero-waste growth’ are being freely used across the world even in serious scientific forums [72–76], no life form can exist for any significant period of time without generating some waste. As for ‘zero waste growth’, it is simply impossible to attain as long as the laws of thermodynamics continue to hold true. The Second Law of Thermodynamics decrees it impossible to have any organism or machine operating at 100% efficiency. Hence it is impossible to operate any system, whether it is engaged in production or pollution control, without some waste of energy or materials.

If a discarded item can be reused without any processing, there would be no immediate generation of waste due to the reuse. But all reused items have a finite life after which they would turn to waste. Hence reuse can at best postpone the eventual production of unusable waste. Over the ‘life, rebirth, and final death cycle’ of any product, waste generation is an absolute certainty. But in most situations recovery, recycle or reuse involve one or other kind of processing which are inevitably accompanied by consumption of energy and wastage of some material, in conformity with the Second Law of Thermodynamics. Hence resource recovery, reuse, or recycling at best prolong the life of a product—that, too, with the accompaniment of energy consumption and waste generation—but can never lead to a ‘zero waste’ existence. It holds true even more strikingly when any new product is made. By technological innovations and adaptation of conservations measures, the production of any good can be made ‘cleaner’ than an alternative made of production but can never be mode perfectly ‘clean’.

In both eco-cities it was planned to recycle and reuse all waste water and solid waste. The planners had assumed that such an intention was by itself adequate to preclude waste generation. They had also not budgeted for the fact that with every incremental step of resource purification attempted (Fig. 2), the cost of treatment rises not linearly but exponentially as one tries to completely remove a contaminant [77,78]. For example the prospect of converting toilet flush into drinking water may be very enchanting, but the cost is not only prohibitive, the overall process ends up generating substantial pollution due to its dependence on energy and materials.

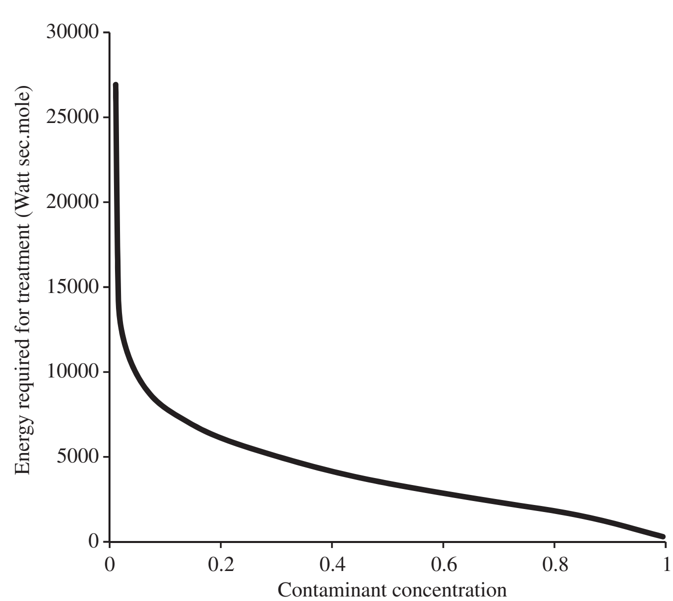



**Fig. 2.** The pattern of increase in the energy required as one approaches a total removal of any contaminant [77].

For solid waste management, Masdar City intends to do incineration, plastic reuse, metal recycling, composting, etc. Each of these processes is either a net energy consumer or leaves one or the other pollutant to contend with. Masdar City's business-houses and residents will use cell phones, computers and all other gadgets that are used in commercial establishments. The resulting e-waste would enhance energy consumption of Masdar City substantially if the city chooses to fully ‘clean’ and reuse its entire e-waste [79]. This will not only enhance the carbon debt of the city but eventually generate nearly as much waste as it would treat. Hence Masdar City can be ‘zero waste’ only by exporting its waste.

The second myth, which had misled the planners of the Dongtan and the Masdar cities equally is that renewable energy means totally clean energy which is not only free of carbon emissions, but also does not produce significant quantities of other forms of waste.

Believing in this myth, the planners of the two eco-cities had assumed that whatever power they will generate through renewable energy sources will be necessarily carbon neutral and shall also not leave any ecological footprint.

The fact is that no renewable energy source, with the possible exception of solar radiation directly used as a source of light or warmth, is carbon neutral or waste-free [80–85]. Generation of power with renewable energy sources also has the potential of seriously interfering with ecosystem services when done at scales comparable with fossil-fuel based power generation [86–90]. There are other problems, mainly caused by low energy density and lack of portability of renewable energy sources. These are compounded further due to the intermittency of some of the sources, such as solar and wind.

All these factors conspire to put unforeseen obstacles in the path of large-scale use of renewable energy sources. For example when Masdar city began efforts to commission its solar photovoltaic (PV) power plant at the chosen site—which is a few kilometers away from the site of Masdar City—it was seen that the desert dust quickly coats the panels, creating an effect similar to that of clouds which reduce the intensity of light falling on the PV cells. Another unforeseen obstacle is caused by the absorption of solar heat by the dark sides of the solar panels, raising their temperature to near 80 °C, and reducing their efficiency [40]. At times the combined effect of ambient dust and heat absorption reduces power output from these PV modules to 40% below capacity [51]. Worse, occasional sandstorms leave solar panels inoperable, requiring expensive use of water and labor for clean-up [60,69].

By early 2010 the Masdar managers had conceded that much of the electricity for their eco-city will have to be imported (from the mainly fossil-fuel powered Abu Dhabi grid) rather than generated locally with renewables.

Significantly, even if problems of these kinds had not arisen and had Masdar City succeeded in its original plan to generate all its power needs with renewable energy sources, it still would have been far from ‘zero carbon’. In fact even before the first occupant moved into Masdar City, the city had incurred a substantial carbon debt in the form of greenhouse gas (GHG) emissions entailed in planning, designing and the initial constructions in the city [91]. From then on this debt has increased by the minute. Whatever power Masdar City has generated or will generate from renewable energy sources has emissions associated with it. Battery-operated vehicles (of the type PRT consists of) are arguably bigger net GHG emitters than fuel-efficient, gas-driven cars [79]. Moreover, contending with emissions that occur in the course of generating energy is only one dimension of the problem. The other, equally challenging dimension of the problem is the emissions occurring when the energy is put to use. And this, second dimension is independent of the first. Given this reality, Masdar City can be zero carbon only in the sense that the GHGs generated due to its construction and functioning will not be emitted in its premises, but some distance away from it. In that sense Masdar City, or the Dongtan City (if it gets revived) will be no different than any well-appointed neighborhood of air-conditioned multi-storied buildings–very clean and comfortable for its occupants or visitors but causing massive environmental damage elsewhere.

Besides the basic flaw in aiming at an unattainable zero-waste existence, Dongtan and Masdar eco-cities have also turned out to be much less attractive (and saleable) pieces of real estate than was hoped. The reason is that in order to meet the lower material/energy consumption targets that define an eco-city, its residents are mandated to adjust with lesser ‘comforts’ than they are used to. For example if Masdar City has to achieve a more energy-efficient and less polluting existence than other cities of the United Arab Emirates its residents will have to follow a life-style which would be different from the more consumerist life style they have been accustomed to. For example the combination of innovative architecture and town-planning coupled with energy-frugal air conditioning will bring the temperatures inside the buildings down to 25 °C which may be comfortable enough but will be way short of the 15.5 °C temperatures most Abu Dhabi residents prefer [50]. As Masdar City was originally planned, it would not have been possible to step out of the office and into a chauffeur driven car to be taken to the next destination. Instead one would have had to use the PRT system to move out of Masdar City before getting access to one's personal car. In several other ways the ‘comfort levels’ at Masdar City will have to be scaled down in proportion to the energy saving that is envisaged. The behavioral regulations and living by a strict ‘rule book’ it requires is not very attractive to those who have the resources to maintain a more free and ‘comfortable’, albeit highly wasteful, life style. In that respect proximity to Shanghai of Dongtan City and to Abu Dhabi of Masdar City have turned out to be more a disadvantage than the boon it was expected to be. Those who have sufficient money to acquire space in the free and serendipitous environment of the bigger cities have no incentive to opt for a more restrictive and frugal life-style of an eco-city—however clean/green and sustainable the latter is touted to be. If Shanghai has become a metaphor for exceedingly ostentatious runaway growth, UAE consumes more energy per capita than even USA, Canada, and all other European countries, except Iceland [92,93]. In a few years, while the citizens of Masdar City will be hard at adjusting their activities to the limited ration of energy and water allotted to them by the city's managers, an up-and-coming Ferrari World theme park near it, 4 times the size of Masdar City will be offering consume-as-much-as-you-please quantities of energy and water for all kinds of water sports in air-conditioned comfort. A 700-store supermall, which is also coming up near Masdar City, will burn up more barrels worth of petroleum in a day than that which the residents of Masdar City will do in several weeks. A Yas F1 race circuit is also coming up [61]. Hence even as Masdar City will struggle to find profitability in conservation, consumption-oriented business will thrive around it, at scales large enough to dwarf the former. In that sense Masdar City will be like a laid-back village employing low-cost materials and saving on energy [94], while hyper-consumptive urbanization will swamp it on all sides.

Which of the two development models will inspire the rest of the world? By all indications Masdar City may prove no more effective than Dongtan City has proved to be in attracting the kind of investment Shanghai or Abu Dhabi are able to muster. Not, atleast, in the near future. Later, when fossil fuel use becomes prohibitively costly, or impossible to continue at the present rate due to increasingly severe impact of global warming, this scenario might tilt on the side of the eco-cities.

## 7. Path to 'low-carbon low-waste' existence

So far this review has been devoted to highlighting that the visions of 'zero carbon–zero waste' eco-cities were doomed to fail because zero-waste existence is impossible while zero-carbon existence is unattainable unless we precipitously reduce energy and material consumption while putting in place strategies to sequester whatever anthropogenic carbon that does get emitted.

In other words even as 'zero carbon–zero waste' existence is not possible, 'low-carbon low-waste' existence very much is. More significantly, to achieve not only low-carbon low-waste existence but also steady growth in that mode, it is not necessary to *ab initio* build eco-cities; the goal can be pursued even in existing cities, towns, and villages. Greater reliance on mass transit systems, better planning of new neighborhoods and dwellings, reducing wastage of energy and materials in day-to-day existence are among initiatives that can be taken by anyone anywhere. New suburbs in existing cities can come up like substantially self-sufficient villages with city-like amenities but more resource efficient and less congested life style [95]. Open spaces can be created in existing cities as was, for instance, accomplished in Boston by moving a major above-ground highway underground. Several cities are trying to decongest by replacing use of cars with public transportation [96]. China has decided to limit introduction of new cars in its capital to a pre-determined number which will be allotted to applicants on the basis of a lottery [97]. Los Angeles is reviving its once extensive light-rail system [98]. There is increasing emphasis on rainwater harvesting [99] and energy conservation. Even the Empire State Building has been refurbished to bring its energy use down by 38% [55]. So far these conservation-oriented attempts have been few, far between, and too sparse (in comparison to the relentless pile-up of consumption-oriented projects across the world) to make a discernable impact. Yet their potential to make a positive impact at the global level is much larger than that which a few eco-cities can accomplish. Doing it will require some self-discipline, some departure from well-set habits, and some feeling of 'restriction'. But all that will be necessary if one has to live even in a most fashionable and expensive eco-city; without restricting consumption no eco-city can be any more 'sustainable' than the present-day megacities are.

It can even be said that liberal use of absurd terms like 'zero carbon–zero waste' building/cities should be avoided as it misleads laypersons as well as policy makers into believing that it is possible to maintain the present-day consumerist life-style and yet achieve 'clean' development. In the like manner it is dangerous to create an impression that a shift from fossil fuels to renewables would foster environment-friendly growth if the present *rate* of increase in energy and material consumption is maintained. A shift to renewables can be helpful only and only if it is accompanied by a drastic cut in energy and material consumption across the world.

## 8. Summary and conclusion

The paper traces the history of two projects which were initiated to develop a model eco-city each in China and Abu-Dhabi. Of these, the former, named Dongtan City, was aimed to be the world's first-ever zero carbon eco-city while the later, the Masdar City, was touted as the world's first ever 'zero carbon–zero waste' city.

Both projects were launched by the governments of the respective countries with great fanfare and promise. Both were expected to provide models of clean and sustainable existence for the rest of the world to emulate. But no sooner that ground was broken to initiate the two cities the unviability of zero carbon–zero waste goal begin to emerge in ever greater relief. Even the low carbon–low waste life style appeared increasingly difficult to achieve because it was more expensive than conventional life style and more restrictive as well.

The paper brings out how the two projects could not take off because they were built on the premise that renewable energy is emission-free. It is not. The other major premise that pollutants can be totally recycled or reused leaving no net waste was also flawed because the second law of thermodynamics makes such an attainment impossible.

The paper also brings out that it is not possible to reduce carbon emissions, nor reduce pollution significantly, as long as cities continue to employ energy and materials as wastefully as is occurring at present. Nor can eco-cities replicate, let alone enhance, consumerist existence and still hope to remain clean, green *and* economically viable. Parallely, the aspects of living that can make any eco-city viable—less energy/material consumption and public participation towards achieving it—can enhance the sustainability of even conventional cities.

## Acknowledgment

SMT thanks the Council of Scientific and Industrial Research (CSIR), New Delhi, for Senior Research Associateship. MP, TA and SAA thank Department of Biotechnology, Government of India, for support.

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